IPAC23 contributions on Final Cooling

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International MUON Collider Collaboration

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COMPARISON OF TRACKING CODES FOR BEAM-MATTER INTERACTION *

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THERMODYNAMIC CHARACTERISTICS OF HYDROGEN IN AN IONIZATION COOLING CHANNEL FOR MUON COLLIDERS *

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Overview

1) Comparison of RF-Track with ICOOL & G4Beamline

- Benchmarking:
  - Energy loss
  - Straggling
  - Scattering

2) Thermodynamics of liquid H absorbers

- Last cell of the a final cooling section

Part 1

Simulation tools for Ionization Cooling (IC)

ICOOL [1]

G4Beamline [2]

RF-Track [3]

- Overview of charged particle interactions implemented in RF-Track
- Benchmarking RF-Track results with ICOOL and G4Beamline

Short overview about RF-Track

Created by A. Latina from CERN

Specialized in optimization of low energy linacs in space charge and other collective effects

Studies trajectories of particles with arbitrary charge and mass transported through conventional elements and field maps

Written in C++ and uses Python and Octave as user interface

Implementation of beam-matter interactions is also useful for radiation oncology treatments

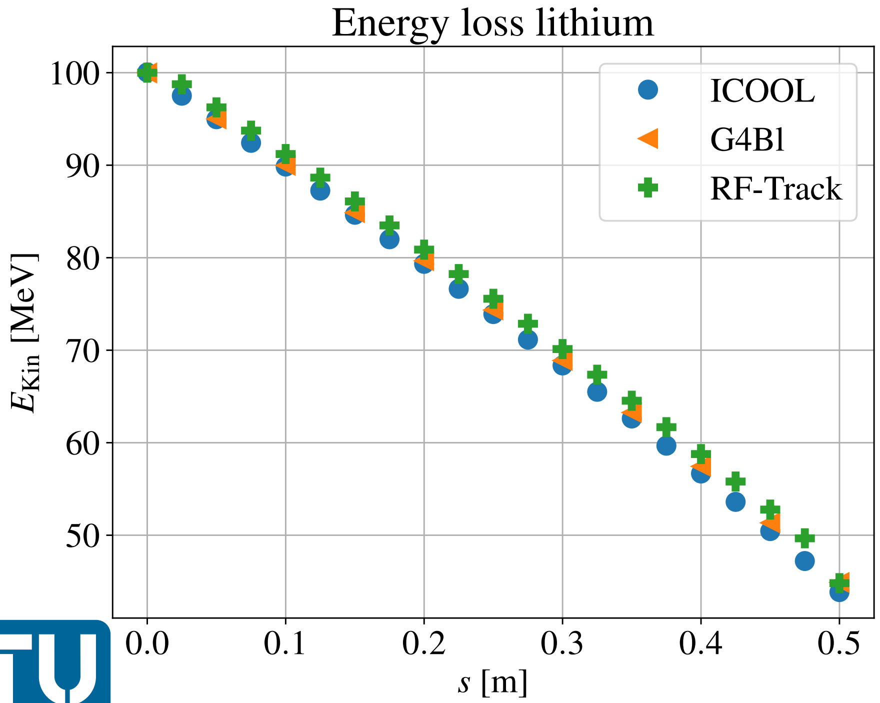
Charged particle interactions in matter

Energy loss

Energy straggling

Multiple Coulomb scattering

Energy loss



Bethe-Bloch equation:

$$-\left\langle \frac{\partial E}{\partial s} \right\rangle = K \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln\left(\frac{2 m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} \right) - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

Energy loss of muons depends on:

- Energy of the particle
- Material properties
- Path length

All 3 programs have consistent values for energy losses in Lithium

Energy straggling

Beam energy range for final cooling is 5-200 MeV.

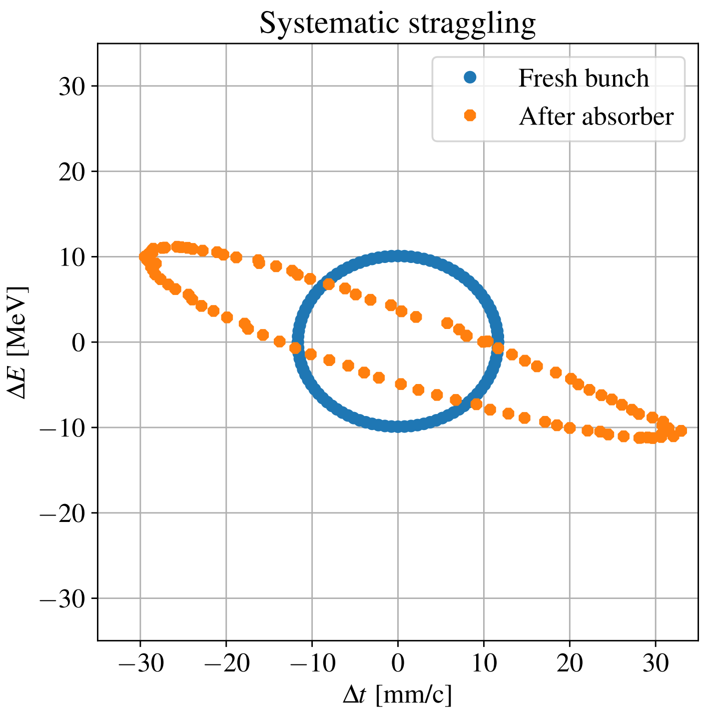
The energy spread in final cooling of the bunch is growing, when muons penetrate an absorber

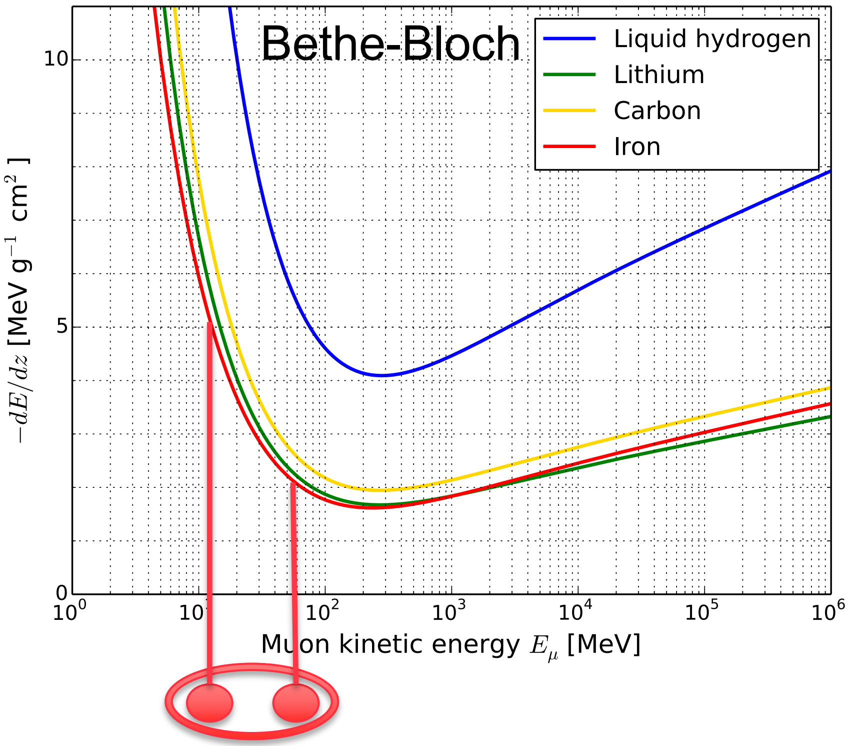
The following effects are driving the energy spread:

Systematic straggling

Stochastic straggling

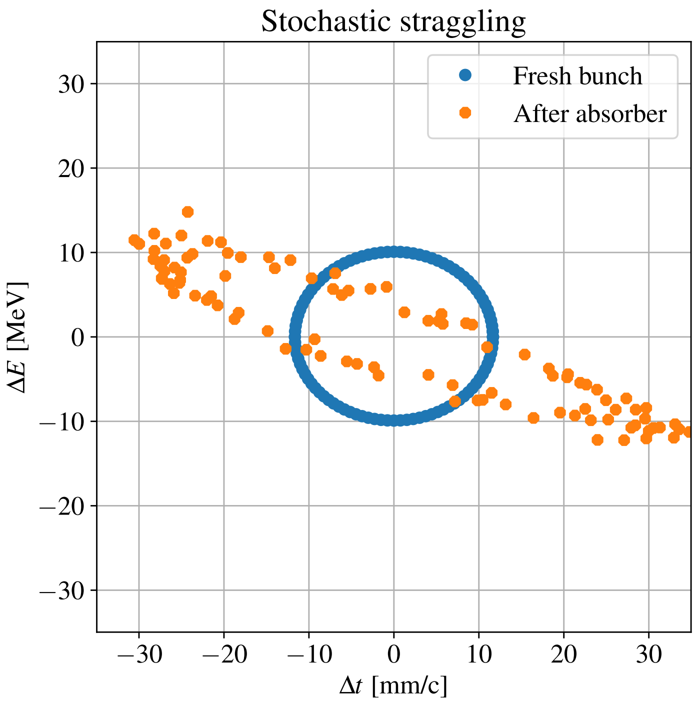
Systematic straggling





$$\frac{d\sigma_E^2}{ds} \approx -2\frac{d\langle \partial E/\partial s\rangle}{ds}\sigma_E^2$$

Stochastic straggling



Approximate absorber as free electron gas

At a certain probability: direct collisions with absorber electrons

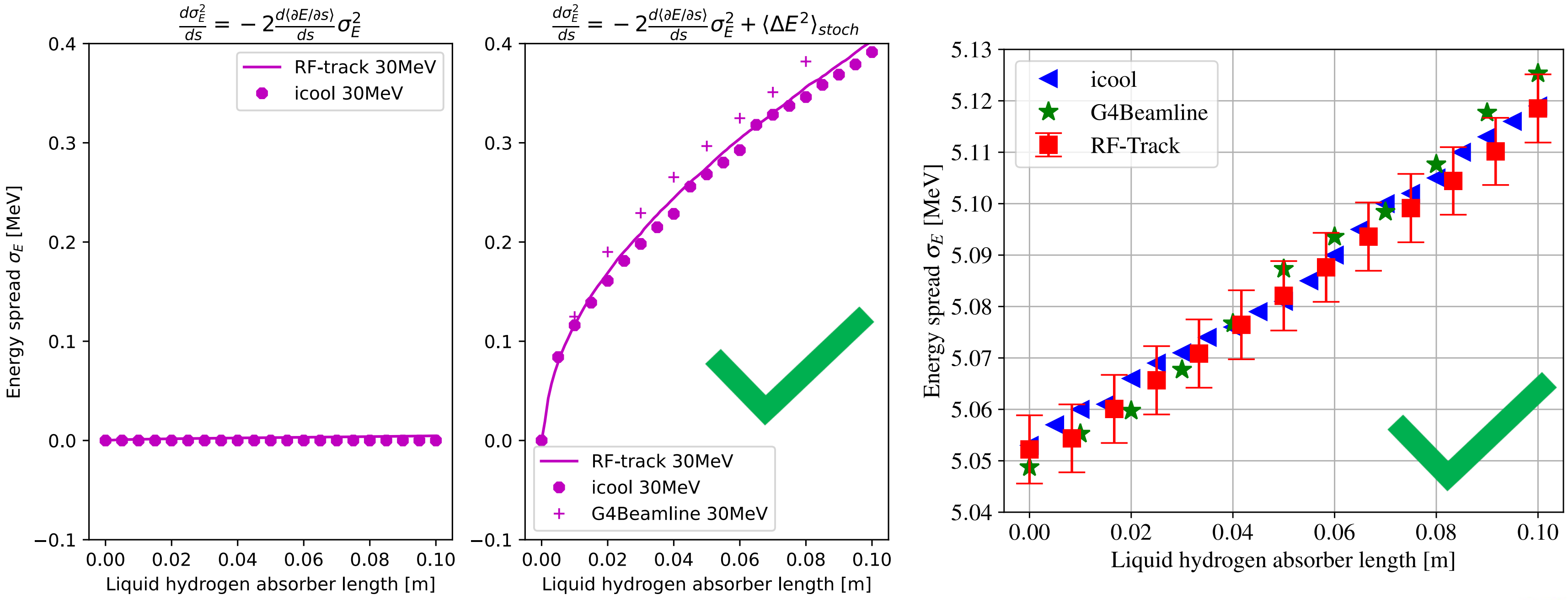
The term is an additional increase of the energy spread

$$\frac{d\sigma_E^2}{ds} = kz^2\frac{Z}{A}\rho\gamma^2\left(1 - \frac{\beta^2}{2}\right)$$

k = 0.153 MeV cm^2 mol^{-1}
ρ… density
Z… atomic number
A… atomic mass
β, γ… Lorentz factors

Straggling benchmarking

$$\frac{d\sigma_E^2}{ds} = -2\frac{\langle \partial E/\partial s\rangle}{ds}\sigma_E^2 + kz^2\frac{Z}{A}\rho\gamma^2\left(1-\frac{\beta^2}{2}\right)$$



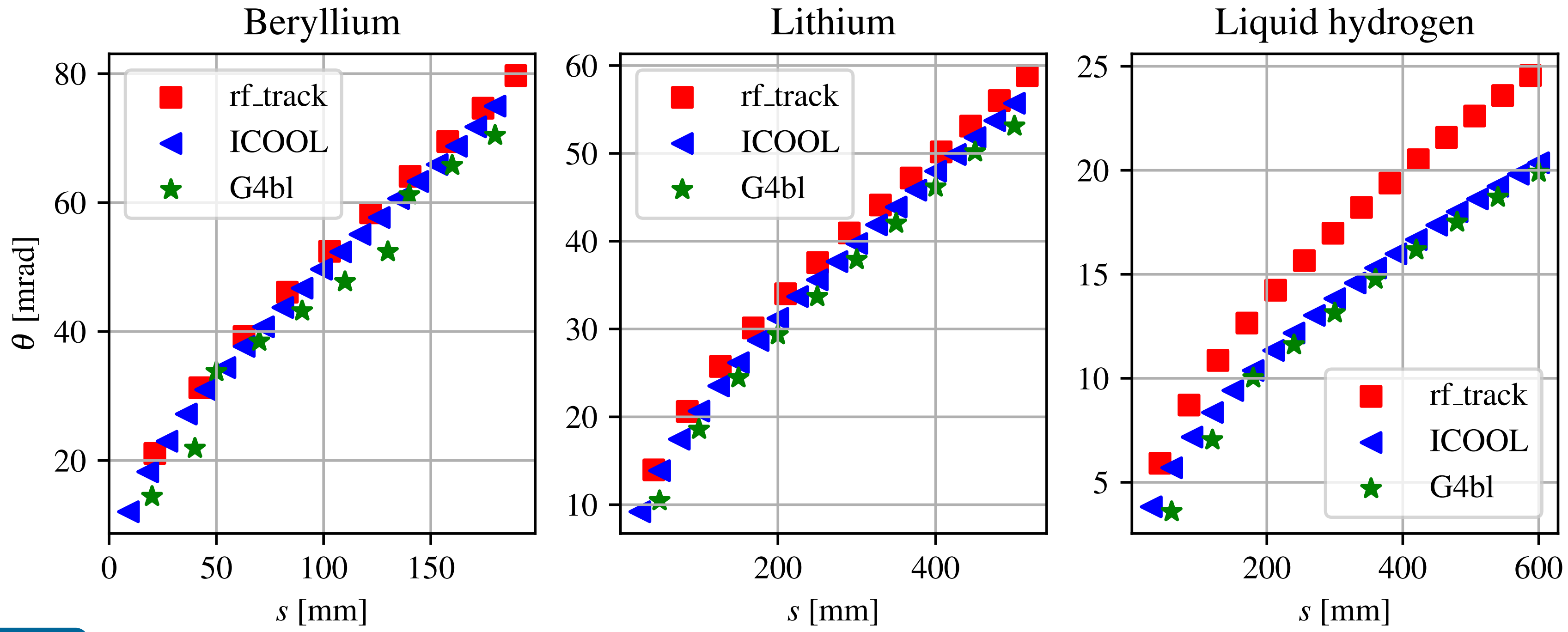
Multiple Coulomb scattering

- Charged particles are deflected by the Coulomb potential of the nuclei in absorbers.
- The sum of nuclear deflection is called Multiple Coulomb Scattering

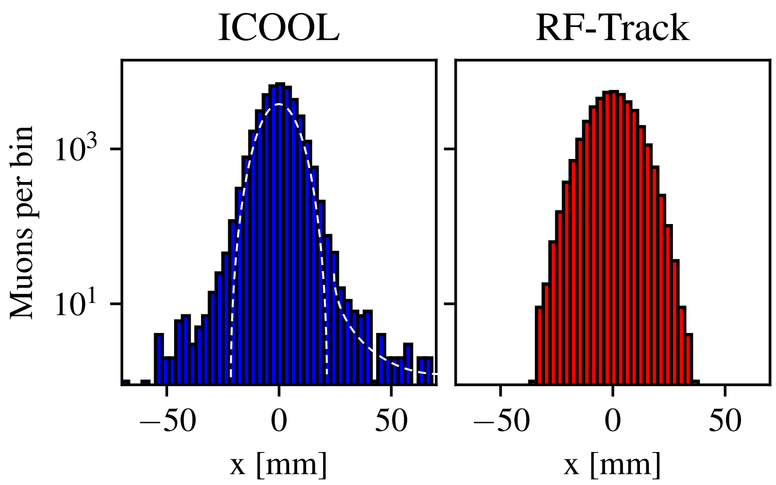
$$\theta = \frac{13.6[\mathrm{MeV}]}{\beta p c} z \sqrt{\frac{s}{L_\mathrm{R}}} \left[1 + 0.038 \ln\left(\frac{s}{L_\mathrm{R}}\right)\right] \quad [4]$$

- Scattering angle distribution approximates a Gaussian
- The logarithmic term is excluded due to discrepancies of the scattering angles for changes in the simulation step size.

Multiple Coulomb scattering benchmarking



Scattering benchmark interpretation



- Discrepancies between RF-Track and ICOOL/G4BL appear for very low Z-material
- Non-Gaussian tails of the distribution are included in ICOOL and G4Bl

First conclusion

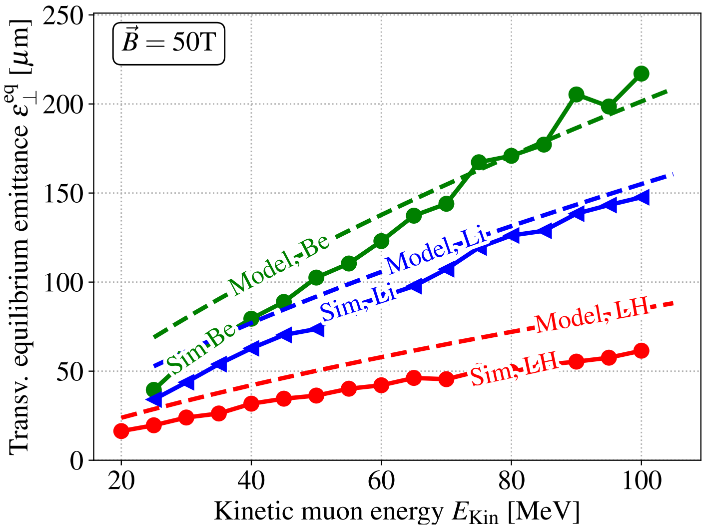
Energy loss, energy straggling & multiple scattering of charged particles were implemented in RF-Track.

Results from energy loss & straggling effects of RF-Track are in good agreement with corresponding ICOOL & G4Beamline simulations.

Scattering angles are overestimated in RF-Track for very low Z-absorber. The next step is to include the hard scattering of charged particles with absorber nuclei.

Part 2

Last cooling cell in the final cooling section



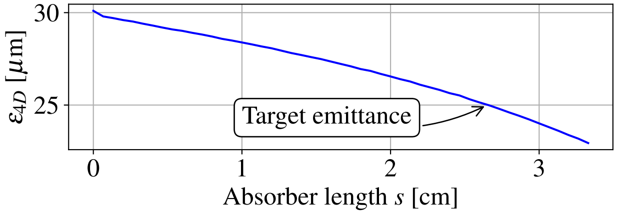
- Transverse target emittance of 25 microns is achieved in the last cooling cell
- Equilibrium emittance estimates the required parameters

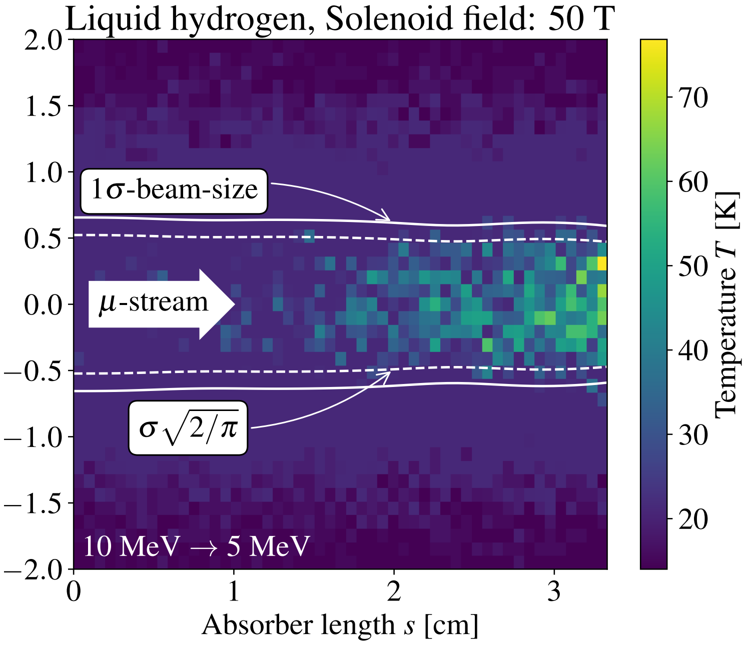
Liquid hydrogen (LH)

Low beam energy

High magnetic solenoid field

Last cell





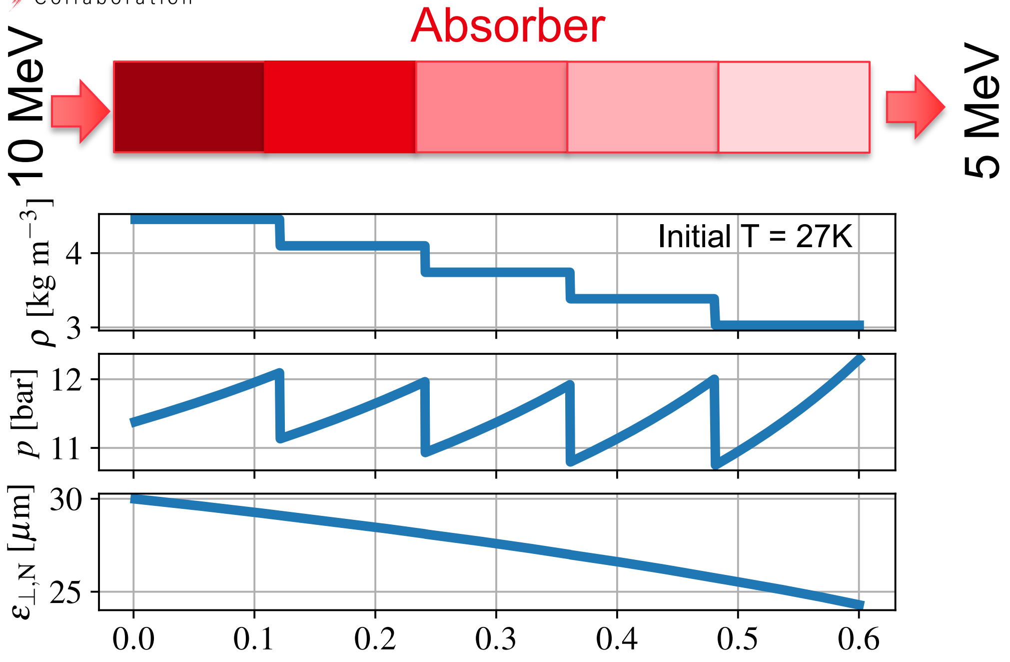
Strong energy deposition inside LH

Temperature increase of up to 70K

Evaporation of LH and high Temp cause pressure increase (>50 bar)

High gas pressures are problematic for thin beam windows

LH absorber alternatives



- Divide absorber in chambers filled with H gas
- Each chamber has different gas densities
- Reduce densities with decreasing emittance
- Reach target emittance within 60 cm length
- Absorber length is limited by solenoid size

Second conclusion

Liquid hydrogen evaporates at very low transverse emittances.

The pressure increase could damage the thin beam windows.

Absorbers with different gas densities avoid extremely high pressure rises.

Reference list

[1] R. Fernow, "COOL: a simulation code for ionization cool- ing of muon beams", *Proc. of the 1999 Particle Accelerator Conference*, New York, NY, USA, 1999, pp. 3020-3022 vol.5, doi:10.1109/PAC.1999.792132.

[2] T.J. Roberts, "G4beamline simulation program for matter- dominated beamline", IEEE Particle Accelerator Conference (PAC), Albuquerque, NM, USA, 2007, pp. 3468-3470, 2007, doi: 10.1109/PAC.2007.4440461.

[3] A.Latina,*RF-TRACK*, https://gitlab.cern.ch/alatina/rf-track-2.0.

[4] H. Bichsel P. Saxon, "Comparison of calculational methods for straggling in thin absorbers", *Physical review A, vol. 11*, 1975, doi:10.1103/PhysRevA.11.1286.

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Thank you for your attention

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